NASA NGST Annual Technology Challenge Review #1

Commercial Development of Terbium-Based Giant Magnetostrictive Alloys for Cryogenic Applications

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History

- 1965: Giant Magnetostriction measured in the basal planes of rare earth metals Terbium (Tb) and Dysprosium (Dy)

  at Naval Ordnance Lab (NOL) and Ames Laboratory, D.O.E.

  Strains approaching 1% (10,000 ppm)

  at low temperatures persist at the

  0.6% (6000 ppm) level up to about 150 K
- 1970's: Room Temperature Giant Magnetostrictive TERFENOL-D developed at NOL

- 1980: Processes to produce high performance transducer elements from these alloys developed
at Ames Laboratory
- 1986: Commercial volume production of TERFENOL-D by ETREMA Products, Inc.
  - $Tb_x Dy_{1-x} Fe_{1.9-1.95}$, x=0.35 to 0.27
  - Rare Earth Metals Tb (Terbium)
  and Dy (Dysprosium) alloyed with Fe (Iron)

- 1990's: Cryogenic alloys researched

  – $Tb_x Dy_{1-x}$ Single crystals of hexagonal close-packed (hcp) Binary Solid Solution Alloys

  – $Tb_x Dy_{1-x} Zn$ Single Crystals of body-centered cubic (bcc) Intermetallic Compounds (in progress)

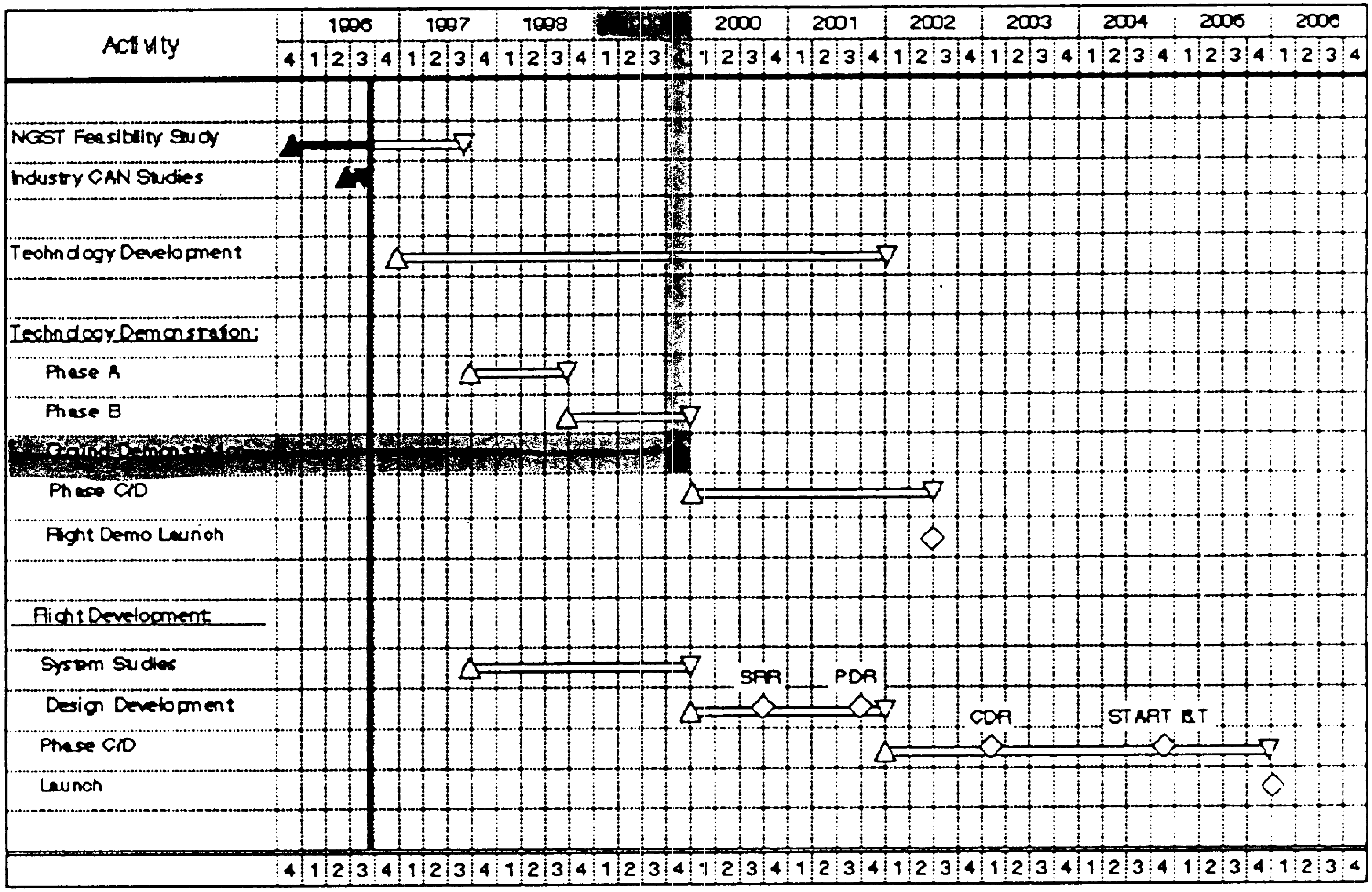
  – $Tb_x Dy_{1-x} Fe_{1.9-1.95}$ (TERFENOL-D) where $x=1.0$ to 0.4 face-centered cubic (fcc) Laves phase Intermetallic compounds (in progress)

Needs

- Increasing number of potential applications for actuation at cryogenic temperatures but materials are not available
- NGST Mirror Manipulators will require commercial quantities of cryogenic materials but processes are not developed
- Major effort needed to develop commercial volume processes in time to meet NGST scheduled demonstration in 4th quarter 1999.

NGST

NGST Schedule



Status

WHAT HAS BEEN ACCOMPLISHED TO DATE

- TERFENOL-D, $Tb_x Dy_{1-x} Fe_{1.9-1.95}$, where x=0.4 to 0.27, stoichiometries used in devices operating in the -60°C to 100°C range.
  - Large-scale production capabilities at ETREMA
    - Near-single crystal <112> crystallographic direction aligned along the drive axis produced by the free stand zone melt (FSZM) crystal growth method with diameters between 2 and 7 mm and lengths of 250 mm
    - <112> directionally solidified large diameter (10 mm to 65 mm) drivers produced by the modified Bridgman (MB) method in lengths of 380 mm

•$Tb_x Dy_{1-x}$ hcp binary alloys

-Research quantities prepared by the strain anneal process. Size limited and required c-axis perpendicular to the drive axis not controllable. Low yields, short lengths and excessive waste due to required machining.

-Moderate success in preparing some aligned polycrystalline sheets by hot rolling and subsequent anneal. Sacrifice in strain (65% of the single crystal strain attained) considered excessive; process not economical on large scale.

- $Tb_x Dy_{1-x}Zn$ bcc Intermetallic Compounds

  - Early success in growing preferred <100> oriented single crystals in sealed crucibles by the Bridgman method

  - Attempts to increase crystal size have not been successful in the laboratory and research is in progress at the Ames Laboratory and NSWCCD to grow and characterize these crystals

ETREMA's PROPOSED APPROACH TO COMMERCIAL DEVELOPMENT

- TERFENOL-D, $Tb_x Dy_{1-x} Fe_{1.9-1.95}$, where x=1.0 to 0.4
  - To be useful at cryogenic temperatures (30 K and below), the terbium content in TERFENOL-D must be increased
  - The Tb-Fe and Dy-Fe binary phase diagrams show that $Tb\,Fe_2$ is more peritectic in nature, which complicates the crystal growth/directional solidification processes currently used to produce high performance Dy-rich (x=0.4 to 0.27) drive elements

- The critical parameters for crystal growth need to be developed for the higher Tb/Dy ratio (x=1.0 to 0.4) materials.
- These alloys could produce strains as high as 5,000 ppm at 30 K, most of which is achieved at practical applied fields (H=1 to 2 kOe).

- $Tb_x Dy_{1-x}$ hcp binary solid solution alloys
  - The reactive nature of the rare earths in their molten state dictates the single crystal growth from the melt by a containerless method.
  - The current strain anneal method is a solid state process which lacks control of the preferred crystallographic (a-axis or b-axis) direction along the drive axis.
  - ETREMA proposes to develop the process to produce these c-axis perpendicular drivers in a controlled manner.

- The largest known magnetostrictions exist in the $Tb_x Dy_{1-x}$ system with strains between 9000 ppm and 6000 ppm acheived in the 0 K to 150 K temperature range.
- Individual drivers are useful for compressive loads up to 25 MPa.
- They can be bundled in laminated form to increase the projection area and extend the frequency range of operation.
- Low hysteretic and low eddy current loss transduction

- $Tb_x Dy_{1-x} Zn$ bcc intermetallic compounds
  - Metallurgical challenge in formation of homogeneous alloys due to high vapor pressure of Zn.
  - Seeded Bridgman crystal growth method being developed at Ames Laboratory with characterization at NSWCCD.
  - ETREMA plans to scale up the process after completion of this R&D effort.
  - <100> crystrallographic oriented single crystals to be produced with easy axis controlled by varying x between 0 and 0.4 in the $Tb_x Dy_{1-x} Zn$ system.

– Large strains between 4500 ppm and 6500 ppm can be achieved at low applied fields, with loads up to 60 MPa 0 K to 150 K temperature range.

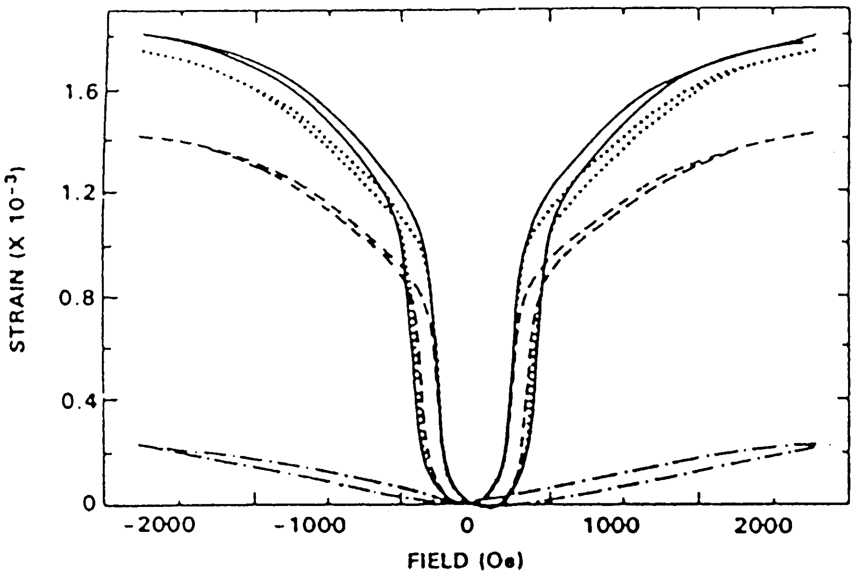


Fig. A. Magnetostriction curves of $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ at 13.3 MPa compressive stress -50°C (dot-dashed curve), and 0°C (solid curve), 20°C (dotted curve), and 80°C (dashed curve)

Clark, Teter, and McMasters , J.Appl. Phys., Vol.63, No. 8, 15 April 1988

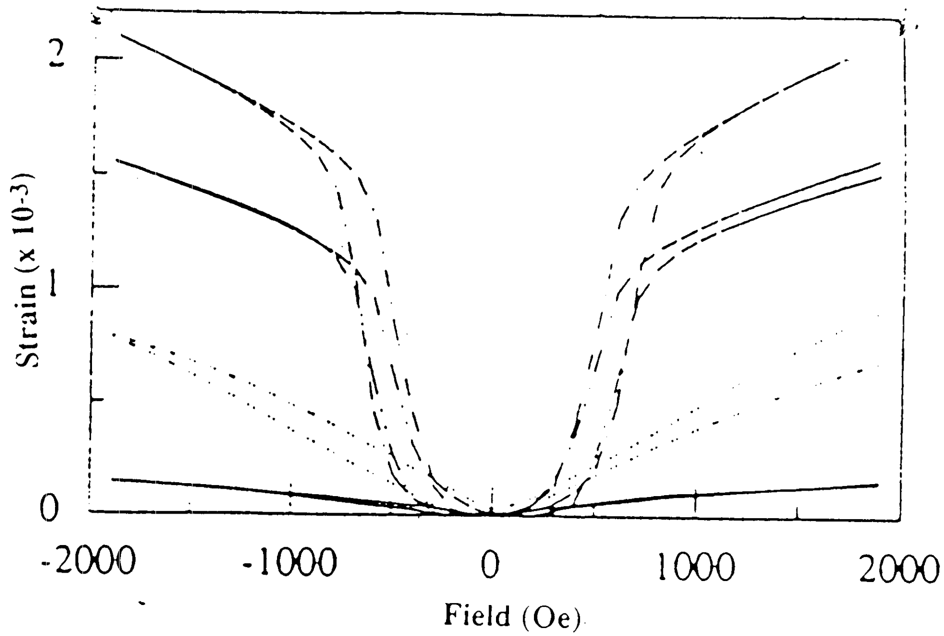
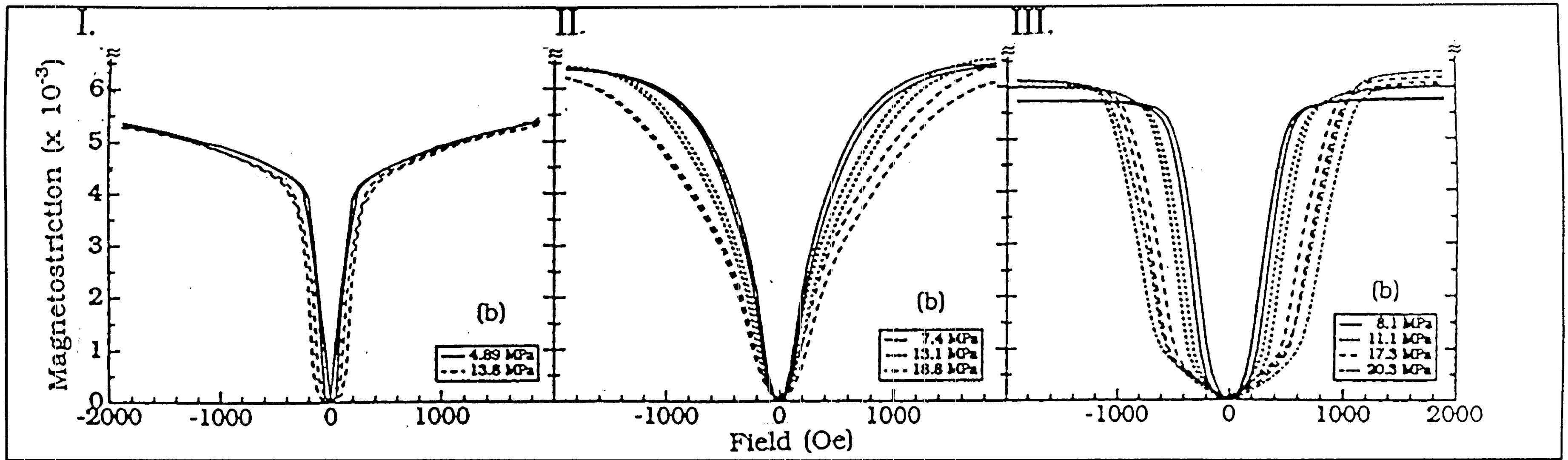


Fig. B. Magnetostriction of $Tb_{0.35}Dy_{0.65}Fe_{1.9}$ under a compressive stress of 15.7 MPa: (a) -196°C (solid curve), (b)-116°C (dotted curve), (c) -68°C (dot-dashed curve), and (d) +24°C (dashed curve).

Clark, Teter, and Wun-Fogle , J.Appl. Phys. Vol. 69, No.8, 15 April 1991



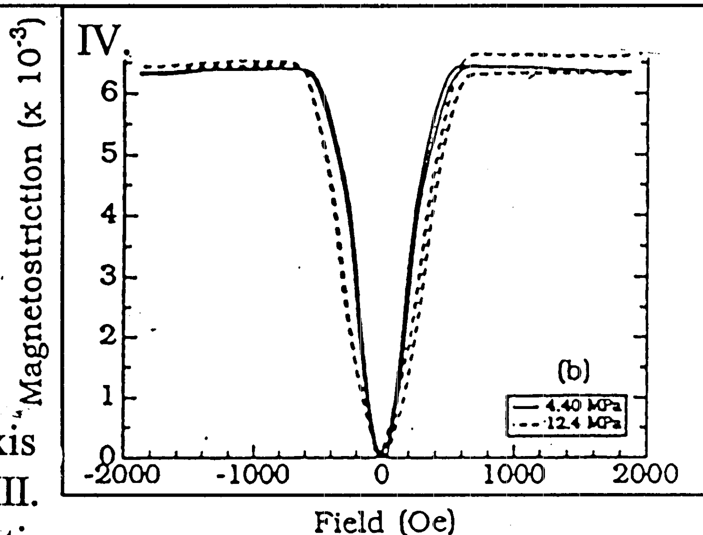


Fig. C. Magnetostriction of b-axis rods: I. $Tb_{.5}Dy_{.5}$, II. $Tb_{.6}Dy_{.4}$, III. $Tb_{.67}Dy_{.33}$ at 77 K. Magnetostriction of an a-axis rod: IV. $Tb_{.6}Dy_{.4}$ at 77 K.

A.E. Clark, M. Wun-Fogle, J.B. Restorff and J.F. Lindberg, IEEE Trans. on Magnetics, 28, No.5. Sept. 1992 p.3156.

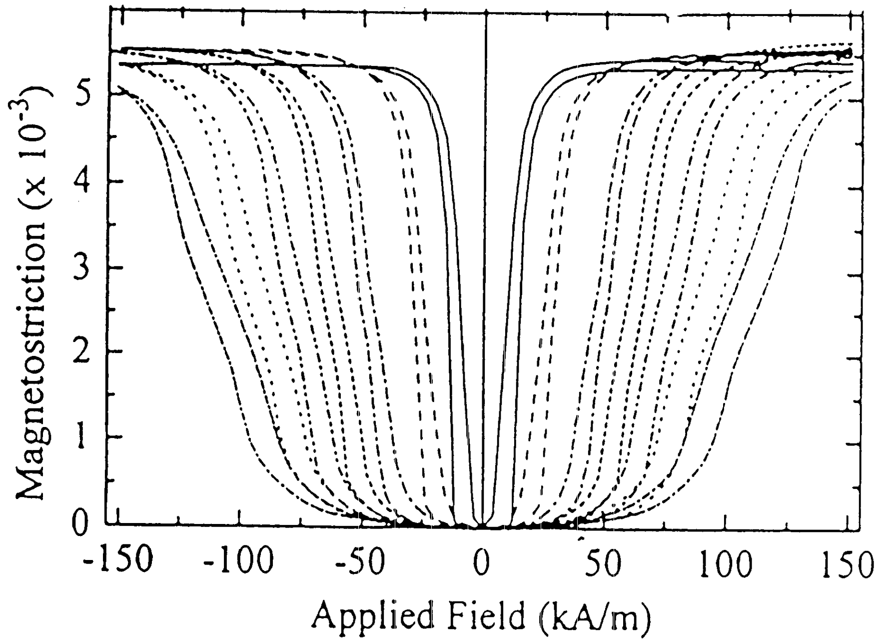


Fig. D. Magnetostriction of single crystal TbZn along the easy [100] axis at 77 K for compressive stresses of 5.3 MPa ———, 13.3 MPa — — —, 24.6 MPa ·—·—·, 31.1 MPa ------, 37.5 MPa ··—··—··, 44.0 MPa ······, 50.5 MPa ·-·-·-·-·-·.

A.E. Clark, J.B. Restorff, M. Wun-Fogle, J.F. Lindberg, Journal of Magnetism & Magnetic Materials 140-144 (1995) 1151-1152